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Summary of Preliminary Criticality Analysis for Peach Bottom Fuel in the DOE Standardized Spent Nuclear Fuel Canister

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Abstract

The National Spent Nuclear Fuel Program is developing a standardized set of canisters for Department of Energy (DOE) spent nuclear fuel (SNF). These canisters will be used for DOE SNF handling, interim storage, transportation, and disposal in the national repository. Several fuels are being examined in conjunction with the DOE SNF canisters.

This report summarizes the preliminary criticality safety analysis that addresses general fissile loading limits for Peach Bottom graphite fuel in the DOE SNF canister. The canister is considered both alone and inside the 5-HLW/DOE Long Spent Fuel Co-disposal Waste Package, and in intact and degraded conditions.

Results are appropriate for a single DOE SNF canister. Specific facilities, equipment, canister internal structures, and scenarios for handling, storage, and transportation have not yet been defined and are not evaluated in this analysis. Because these details are not yet available, results are not considered fully validated and are not suitable for establishing operational criticality safety controls. In addition, final DOE SNF canister or Waste Package design, operational considerations, or facility configurations could further restrict the canister loading. A complete criticality safety evaluation, including full validation and contingency and accident analyses, must be completed before Peach Bottom fuel is loaded into the DOE SNF canister.

The analysis assumes that the DOE SNF canister is designed so that it maintains reasonable geometric integrity. Parameters important to the results are the canister outer diameter, inner diameter, and wall thickness. These parameters are assumed to have nominal dimensions of 45.7-cm (18.0-in.), 43.815-cm (17.25-in.), and 0.953-cm (0.375-in.), respectively.

Calculations assumed bare Peach Bottom fuel elements in the small-diameter, 456.9-cm-long DOE SNF canister. Assuming beginning-of-life ^{235}U and maximum end-of-life ^{233}U, the calculated results are: 15 intact elements in the DOE SNF canister, $k_{eff} + 2\sigma = 0.884$; 15 elements in degraded condition in the co-disposal waste package, $k_{eff} + 2\sigma = 0.977$; 14 elements in degraded condition in the co-disposal waste package, $k_{eff} + 2\sigma = 0.954$. If 50 kg of iron in the form of geothite is added, $k_{eff} + 2\sigma = 0.883$ for 15 elements in degraded condition in the co-disposal waste package.

Based on these results, the recommended fissile loading for the DOE SNF canister is 13 Peach Bottom fuel elements if no internal steel is present, and 15 Peach Bottom fuel elements if credit is taken for internal steel.

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Terms and Acronyms

ANS	American Nuclear Society
ANSI	American National Standards Institute
BOL	beginning-of-life (pre-irradiation)
DOE	United States Department of Energy
ENDF/B-V	evaluated nuclear data file/version B-V
EOL	end-of-life (post-irradiation)
HLW	High Level Waste
IFSF	Irradiated Fuel Storage Facility
k_{eff}	effective neutron multiplication factor
MCNP	Monte Carlo N-Particle Transport Code System™
OD	outer diameter
QARD	Quality Assurance Requirements and Description, DOE/RW-0333P
RW	OCRWM, DOE Office of Civilian Radioactive Waste Management
SNF	Spent Nuclear Fuel
SS	stainless steel
Δ	delta, difference
σ	standard deviation

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Table of Contents

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List of Tables

List of Figures

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1.0 Introduction

The National Spent Nuclear Fuel Program is developing a standardized set of canisters for Department of Energy (DOE) spent nuclear fuel (SNF). These canisters will be used for DOE SNF handling, interim storage, transportation, and disposal in the national repository. Several fuels are being examined in conjunction with the DOE SNF canisters.

This report summarizes results from a detailed preliminary criticality safety analysis[1] that addresses general fissile loading limits for Peach Bottom graphite fuel in the DOE SNF canister. The Peach Bottom fuel elements are considered in both intact and degraded conditions. The canister is considered both alone and inside the 5-HLW/DOE Long Spent Fuel Co-disposal Waste Package.

All data pertaining to the Peach Bottom fuel element geometry and material loadings is accurate but considered unqualified. These data were not acquired, developed, or qualified in accordance with an approved quality assurance program that meets DOE/RW-0333P (QARD).[2] Results presented were determined using a qualified code per the QARD, but are not considered fully validated.

Results are appropriate for a single DOE SNF canister. Specific facilities, equipment, canister internal structures, and scenarios for handling, storage, and transportation have not yet been defined and are not evaluated in this analysis. Because these details are not yet available, results are not suitable for establishing operational criticality safety controls. In addition, final DOE SNF canister or Waste Package design, operational considerations, or facility configurations could further restrict the canister loading. A complete criticality safety evaluation, including full validation and contingency and accident analyses, must be completed before Peach Bottom fuel is loaded into the DOE SNF canister.

2.0 Description

2.1 Peach Bottom Fuel Elements[3]

Peach Bottom Unit 1 was a prototype high-temperature gas-cooled reactor. It used graphite moderation with highly enriched uranium-thorium carbide fuel. It operated from March 1966 to October 1974 using two fuel cores. Core 1 had a higher fissile loading and 450 days of exposure. Core 2 had 900 days of exposure. Each core used four types of standard fuel elements: I – heavy rhodium; II – light rhodium; III – light rhodium with poison; and IV – heavy thorium/light uranium. A nominal core loading contained 54 Type I elements, 564 Type II, 84 Type III, and 102 Type IV.

Cores 1 and 2 each had 36 instrumented fuel elements. These looked very much like the standard fuel elements, with the exception of the bottom connector. The modified bottom connector does not have a notched end like the standard bottom connector. All instrumented elements had thermocouples; some were equipped with acoustic thermometers. Instrumented fuel elements have the same fuel loadings as standard fuel elements and were used in place of standard fuel elements.

A total of 34 test elements were irradiated. These differed from the standard fuel elements both in geometry and in material loadings. Test elements are not assessed in this preliminary analysis.

Peach Bottom fuel elements for both cores are stored at the Idaho Nuclear Technology and Engineering Center at the Idaho National Engineering and Environmental Laboratory. Core 1 fuel elements are individually packaged, and stored in canisters at facility CPP-749. Core 2 fuel elements are stored in canisters in the Irradiated Fuel Storage Facility (IFSF) at building CPP-603. Because the IFSF storage canisters are only 335-cm (11-ft.) long, the top 45.7-cm (18-in.) of the upper reflector assembly was cut off before the Core 2 elements were placed into storage.

A Peach Bottom standard fuel element is pictured in Figure 1.[3] It is 365.76-cm (144-in.) long and 8.89-cm (3.5 in.) in diameter. It is constructed almost entirely of graphite, weighing about 41 kg (90 lbs). Axially, the fuel region is nearly centered along the fuel element.

An outer 1-cm (0.4-in.) thick sleeve contains the fuel region. The sleeve is low-permeability graphite with a density of 1.90 g/cm^3. It extends axially beyond the fuel region in both directions, for a total length of 292-cm (115-in.), connecting the fuel region with graphite reflector assemblies. The upper reflector assembly is threaded and cemented into the sleeve. The lower reflector assembly includes a solid lower reflector, an internal fission product trap assembly, and a bottom connector. At the bottom of the fission product trap is a small (5 gram) stainless steel screen. A 15-gram silicon braze connects the lower edge of the sleeve to the bottom connector.

Inside the fuel region of the sleeve are annular compacts of uranium and thorium carbide particles in a graphite matrix, formed by warm-press and sintering. The Core 1 fuel particles have a single coating of pyrolytic carbon. Core 2 fuel particles were fabricated with a low-density inner coating and isotropic outer coating of pyrolytic carbon.

Thirty of these fuel compacts are stacked on a central 4.445-cm (1.75-in.) diameter spine of 1.85 g/cm^3 graphite. The Type 3 element spines are unique in that the spine is annular, containing burnable poison compacts. These spines have a 2.26-cm (0.89-in.) inner diameter. The poison compacts are 5-cm (2-in.) long rods of zirconium diboride in a graphite matrix.

While Core 1 and Core 2 elements have the same outer dimensions, the fuel compacts differ slightly. The Core 1 fuel compacts have axial grooves and are slightly shorter. The Core 2 fuel compacts have small slots in the compact ends. Due to the small variation in compact height, the overall fuel region length is 227.076-cm for a Core 1 element, 228.600-cm for a Core 2 element. The difference in fuel region length is compensated for in the upper reflector assembly.

Four types of fuel compacts were made for each core – standard, heavy rhodium, light rhodium, and heavy thorium. Compacts and spines were assembled in several different combinations to create the four different types of fuel elements. The total beginning-of-life (BOL) loadings for each of the fuel element types are given in Table 1. The uranium and thorium loadings are uniform throughout the fuel region of an element. A uranium isotopic breakdown was not available for the Core 2 elements.

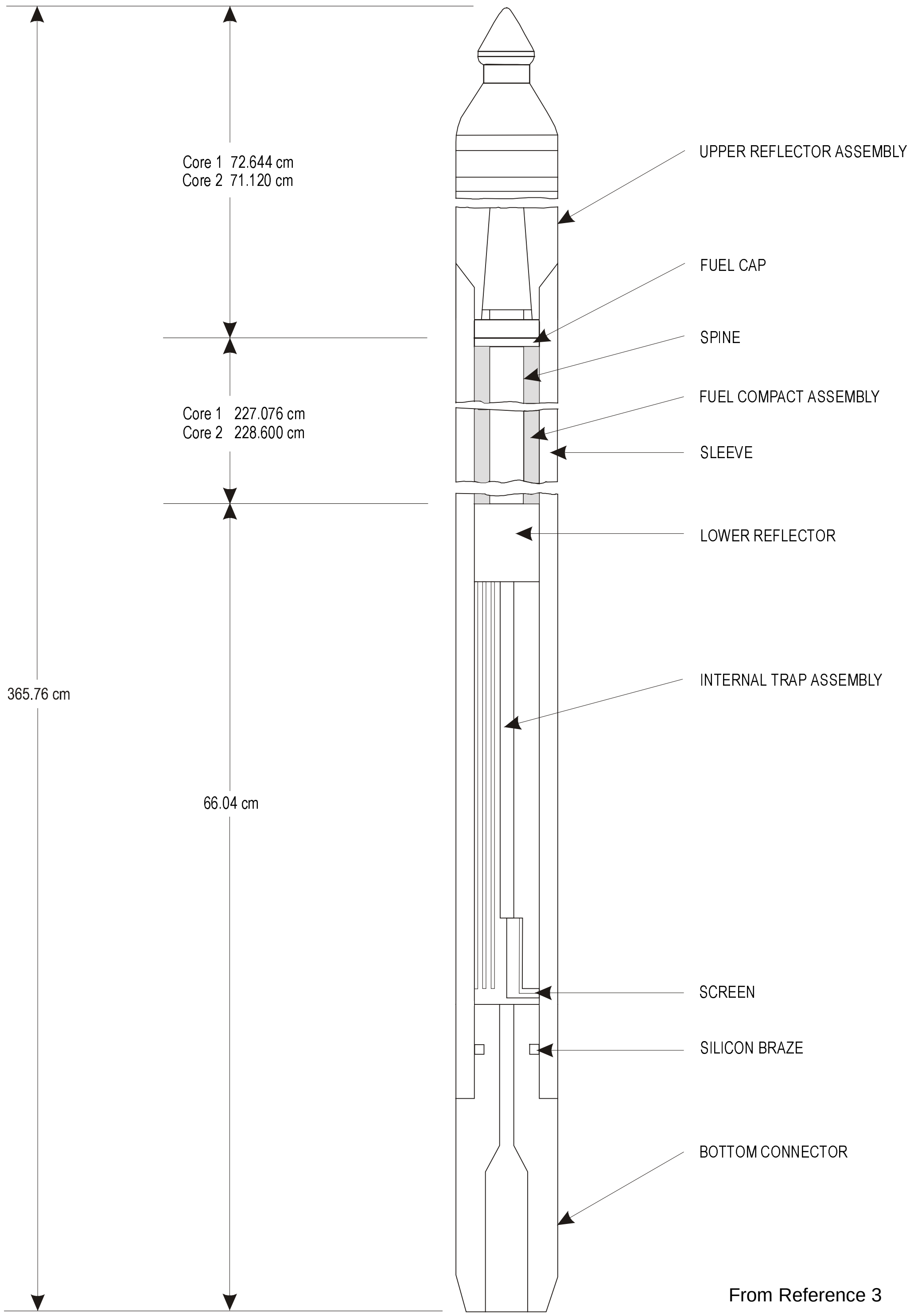

Figure 1. Peach Bottom Standard Fuel Element

Some post-irradiation/end-of-life (EOL) values are specified for the Core 1 and Core 2 fuel. Fuel element average and maximum values are given in Table 2. EOL values for the total core are given in Table 3.

Table 1. Peach Bottom Fuel Elements: Beginning-of-Life Loadings (grams)

Core 1 Fuel Elements					Core 2 Fuel Elements				
	Type 1	Type 2	Type 3	Type 4		Type 1	Type 2	Type 3	Type 4
^{103}Rh	18.5	6.16	6.16	0	^{103}Rh	18.54	6.16	6.16	0
^{232}Th	1563	1563	1563	3460.8	^{232}Th	1374	1374	1374	2598
^{234}U [c]	4.68	4.68	4.68	2.46	U (93.15)	249.6	249.6	249.6	140.7
^{235}U	291	291	291	154.2	^{235}U [d]	232.5	232.5	232.5	131.0
^{236}U [c]	1.56	1.56	1.56	0.84					
^{238}U	15.15	15.15	15.15	8.04					
matrix C	8550	8550	8550	8190	matrix C [d]	8670	8670	8670	8220
^{10}B	0	0	18.3	0	^{10}B	0	0	18.31	0

[a] From reference 3.
[b] From reference 3 unless otherwise noted (see footnote d).
[c] ^{234}U and ^{236}U values are the maximum expected.
[d] From internal letter Rew-5-75, R.E. Wilson, *PTE-1 Peach Bottom Fuel Element Storage CSE*, December 1975, Attachment Table 3.

Table 2. Peach Bottom Fuel Element End-of-Life Loadings

Core 1 EOL Masses (grams) [a]					Core 2 EOL Masses (grams) [b]				
	Types 1,2,3		Type 4			Types 1,2,3		Type 4	
Isotope	Average	Max	Average	Max	Isotope	Average	Max	Average	Max
Total U	268.99	303.81	150.42	155.48	^{232}Th	1310	--	2524	--
^{232}U	0.00163	0.00208	0.00301	0.00326	Total U	167.0	228.7	105.0	108.4
^{233}U	23.87	27.10	34.80	36.28	^{233}U	33.0	35.2	37.8	39.1
^{234}U	3.70	3.89	3.19	3.34	^{235}U	90.0	189.0	36.0	108.4
^{235}U	206.98	268.84	91.71	96.02	Total Pu	0.59	--	0.18	--
^{236}U	18.36	20.76	11.90	12.33	^{239}Pu	0.27	--	0.08	--
^{238}U	16.07	17.10	8.81	8.86	^{240}Pu	0.09	--	0.03	--
					^{241}Pu	0.15	--	0.05	--
					^{242}Pu	0.07	--	0.03	--

[a] Summarized from reference 3 Table 5-7.
[b] From reference 3

Table 3. Peach Bottom End-of-Life Total Core Loadings

Isotope	Core 1 (grams) [a]	Core 2 (grams) [a]
^{232}Th	1439310	1172540
^{232}U	1.46	7.48
^{233}U	20523.82	25945.99
^{234}U	2956.24	4546.84
^{235}U	156518.24	66962.86
^{236}U	14266.21	21116.46
^{238}U	12324.92	9252.53
^{239}Pu	411.17	199.51
^{240}Pu	82.85	69.21
^{241}Pu	63.34	112.47
^{242}Pu	8.31	53.70
^{103}Rh	--	2763.79
^{10}B	--	1.93

[a] From reference 3

2.2 DOE Standardized SNF Canisters[4]

The set of DOE SNF canisters is based on a single design concept that includes radial and axial symmetry, such that it can be handled from either end. The designs differ by canister diameter and length. The two diameters are 45.7-cm (18.00-in.) and 61.0-cm (24.00-in.), the lengths 299.9-cm (118.11-in.) and 456.9-cm (179.92-in.). The large-diameter canister is not examined in this analysis.

The shorter canister is too short to accommodate Peach Bottom fuel elements. The small-diameter, 456.9-cm-long canister has a minimum active storage length of 411.7-cm (162.09 in.). The canister walls are a nominal 0.953-cm (0.375-in.) thick type 316L stainless steel. Each end features a dished head and lifting rings. Impact plates of 5.0-cm (2.00-in.) thick carbon steel are placed in the upper and lower heads at the time of fuel loading.

2.3 5-HLW/DOE Spent Fuel Long Co-disposal Waste Package[5]

The 5-HLW/DOE spent fuel long co-disposal waste package is intended for disposal in the national repository. It has a central support tube that can accommodate a small-diameter (45.7-cm diameter) DOE SNF canister. The central tube is surrounded by five equally spaced storage positions, each of which holds a High Level Waste (HLW) glass-pour canister. The co-disposal waste package has an outer diameter of 212-cm and overall length of 536.7-cm, including 22.5-cm skirts at each end. The outermost corrosion allowance shell is constructed of carbon steel, with 10-cm thick walls and bottom and an 11-cm thick lid. The inner corrosion resistant shell is made of Alloy C-22 (a nickel alloy), with 2-cm thick walls and bottom and a 2.5-cm thick lid. A 3-cm closure lid gap separates the two lids. The inner cavity length is 461.7-cm. The central support tube is constructed of 3.175-cm thick carbon steel. Web-like carbon steel plates connect the support tube to the inner shell and form the five external storage positions. Both the support tube and the plates are 459.7-cm long.

For this analysis, it is assumed that Hanford HLW Glass Pour canisters are in the external storage positions of the co-disposal waste package. These are representative of typical waste glass canisters expected for the long co-disposal waste package. The canisters are constructed of Type 304L stainless steel with an outer diameter of 61-cm and length of 457.2-cm. The wall thickness is 1.05-cm. The total HLW canister weight is 4200 kg, with the waste glass occupying 87% of the volume.

3.0 Requirements Documentation

The Preliminary Design Specification[4] for the DOE SNF canisters asserts that the SNF will be loaded into the canister such that criticality concerns during the canister's design life will be precluded. This can be achieved by proper fissile loading limits, by properly designed internals, or by a combination of both. The specification also states that for criticality concerns, the DOE SNF canister must be capable of maintaining reasonable geometric integrity only.

This analysis is preliminary in nature. As such, standard quality assurance criteria for a typical criticality safety evaluation do not specifically apply, but are invoked voluntarily where appropriate. Criticality safety criteria are contained in national standards ANSI/ANS-8.1,[6] –8.7,[7] and –8.19,[8] standard DOE-STD-3007-93,[9] and 10 CFR parts 60, 61, 71, and 72. The analysis is required to be well documented, have a validated calculation method and verified software code, and to be independently reviewed. To be considered well documented, an analysis must be reported in sufficient detail to allow independent judgment and reproduction of results by a qualified criticality safety analyst. A documented criticality safety analysis is required to demonstrate fissile systems will be subcritical under normal and credible abnormal conditions. Some criteria require limits based on validated calculations not exceed a calculated k_{eff} of 0.95. These standard quality assurance requirements are consistent and compatible with applicable criteria of DOE/RW-0333P, *Quality Assurance Requirements and Description* (QARD) for the Office of Civilian Radioactive Waste Management (RW).[2] The criticality safety analysis summarized in this report is well documented, was conducted with verified software code, and was independently reviewed. The calculation method was validated only partially, but validation was sufficient to provide some confidence in results.

4.0 Methodology

4.1 Calculational Codes and Cross Sections

The calculations for this evaluation were performed using MCNP 4B2, with the ENDF/B-V continuous energy cross section library.[10] Calculations were carried out on a networked system of Hewlett-Packard 9000 series workstations under version 10.20 of the HPUX UNIX operating system. MCNP is a generalized geometry Monte Carlo transport code qualified to comply with QARD requirements.[11] It is considered by the National Spent Nuclear Fuel Program to be transferred software.[12] The local copy of this software and its accompanying data libraries are maintained by RW-qualified personnel.

4.2 Validation

Complete validation for this analysis could not be accomplished because specific facilities, equipment, and scenarios for handling, storage, and transportation have not yet been defined. Several validation cases for the Peach Bottom fuel are included here to provide some confidence in results. It is recommended that, in addition to the experiments presented below, critical experiments with thoria-urania fuel from Argonne National Laboratory[13] be added to the validation. Others should be added as appropriate.

The critical experiments used for initial validation efforts are documented in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*.[14,15,16,17,18] Results indicate that if a bias is necessary, it will not be significant to the extent that it would change the conclusions of this report. All validation cases were run under the RW-qualified version of MCNP with ENDF/B-V cross sections.

5.0 Discussion of Contingencies

A discussion of contingencies is not included in this evaluation because specific facilities, equipment, and scenarios for handling, storage, and transportation have not yet been defined. A contingency analysis must be performed when this information is available.

6.0 Evaluation & Results

6.1 Description of Model

The Peach Bottom fuel element was modelled as a simple cylinder with an outer diameter of 8.89-cm and three axial regions. The axial dimensions were modelled as given in Figure 1. The lower and upper regions were modelled as solid graphite at a density of 1.90 g/cm^3. Non-graphite parts were ignored due to their small size and distance from the element fuel portion.

The fuel region was modelled as concentric cylinders. The sleeve was 1.016-cm-thick graphite at 1.90 g/cm^3. The fuel compacts were modelled as a single annulus, with an outer diameter of 6.858-cm and inner diameter of 4.445-cm. The fuel annulus compositions are shown in Table 4 according to fuel element type. The isotopic mass values are generally average EOL, with the exception of ^{233}U and ^{235}U, which are maximum EOL. The derivation of these values is shown in the detailed analysis.[1] The neutron absorber ^{103}Rh was conservatively omitted from the model. With ^{103}Rh omitted, the fuel annulus compositions for element Types 1-3 were identical. The spine was graphite at 1.85 g/cm^3. It was modelled as a cylinder for fuel types 1, 2, and 4, and as an annulus for fuel type 3. Type 3 fuel elements had an annular spine and a 2.261-cm-diameter central poison rod. The poison rod composition is given in Table 5. The derivation of these values is shown in the detailed analysis.[1] Atom densities for materials were determined in accordance with RW guidance.[19]

Consideration was given to possible water intrusion into the fuel elements. For simplicity it was assumed that void space in the element would be replaced by water for “saturated” fuel. The void space for a dry element was approximately 20%.

Table 4. Fuel Annulus Compositions for Calculational Model

Isotope	Core 1, Types 1-3 [a] (grams)	Core 1, Type 4 [a] (grams)	Core 2, Types 1-2 [a] (grams)
^{232}Th	1536	3402	1310
^{233}U	27.1	36.28	35.2
^{234}U	3.7	3.19	5.807
^{235}U	268.84	117.92	197.30
^{236}U	18.36	11.9	29
^{238}U	16.07	8.81	12.5
^{239}Pu	0.58	0.58	0.27
^{240}Pu	0.12	0.12	0.09
^{241}Pu	0.09	0.09	0.15
^{242}Pu	0.01	0.01	0.07
C	8743.5	8565.2	8839.8

[a] See reference 1 Appendix C for complete derivation of these values.

Table 5. Core 1 Type 3 Poison Rod Composition

Element	Mass (grams) [a]
B	18.3
Zr	77.07
C	1676.6

[a] See reference 1 Appendix C for complete derivation of these values.

The DOE SNF canister model closely follows the design discussed in Section 2. The model differs slightly from the current design in canister length. The model used an overall length of 456.87-cm and interior usable length of 414.45-cm. These slightly larger values are based on an earlier design. Several calculations were done to assess the importance of the canister walls and ends. Results are given in Table 6. It can be concluded that the canister ends, and the slight decrease in the designed canister length, do not affect the calculated k_{eff} of the canister. The canister wall thickness is important, but so long as the wall thickness is at least half of the nominal value, the impact on calculated k_{eff} is small. The canister material is stainless steel type 316L.

Table 6. Calculational results for canister design

Base Case [a]	Description	$k_{eff} \pm 1\sigma$ [a]	Δk_{eff}
0.9084 ± 0.0011	Walls at ½ thickness	0.9135 ± 0.0011	-0.0051
	No canister walls	0.9529 ± 0.0011	-0.0445
	No canister ends	0.9084 ± 0.0011	0.0000

[a] See reference 1 for complete calculations and results.

6.2 Calculations

This section summarizes calculations and results. A full presentation of calculations is contained in the detailed analysis.[1] All calculations used 30-cm of water reflection. Theoretically, the maximum number of Peach Bottom fuel elements that can fit inside the DOE SNF canister is 19. This assumes bare elements with essentially no spacing. It is depicted as the “regular arrangement” in Figure 2. As indicated by the figure, for the 19 elements to be modelled in a triangular-pitched array, the can diameter must be increased. Most cases used 19 elements. When a minimal allowance is included to accommodate deviations in element diameter and straightness, the maximum number of elements that can fit into the DOE SNF canister decreases to 14 or 15 elements. The array used for calculations with 15 elements is also shown in Figure 2.

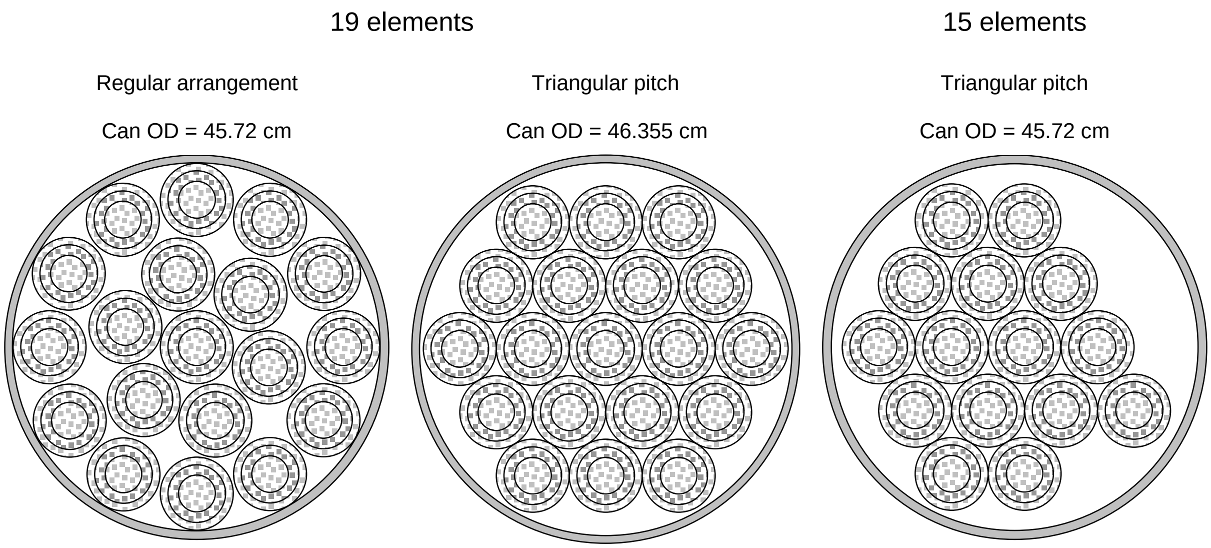

Figure 2. Several element configurations used for calculations

Comparison of fuel elements by type. For this calculation, the regular arrangement of 19 elements in the DOE SNF canister was used. Five fuel element compositions were considered:

1 – Core 1, Type 1 or 2
2 – Core 1, Type 3 with all ^{10}B replaced by ^{7}Li
3 – Core 1, Type 3 with 10% of pre-irradiation ^{10}B
4 – Core 1, Type 4
5 – Core 2, Type 1 or 2

Each composition was modelled for 19 elements with both saturated and dry fuel, and both with and without water between fuel elements. The most reactive composition for all variations was that of Core 1, Type 1 or 2 fuel elements. This composition was used for all subsequent calculations. With the fuel fully flooded, the calculated $k_{eff} + 2\sigma$ is 0.911 (0.9084 ± 0.0011).

Triangular-pitched array of elements. This array was modelled without the DOE SNF canister. First a spacing study using the 19-element array was done. Cases were run both with and without water between fuel elements. The amount of water in the fuel elements was varied in 5% increments, from dry to saturation (~20%). The spacing between elements was then varied from 0- to 4-cm. The maximum calculated k_{eff} results are summarized in Table 7.

Second, beginning with the fully flooded case, the density of the water between fuel elements was decreased. The elements remained saturated and touching throughout. No local minima or maxima in calculated k_{eff} were observed as water density was decreased down to zero. Again, the most reactive configuration was the fully flooded array.

Table 7. Calculated results from 19-element spacing study

Water in fuel	Water between fuel elements [a]			No water between fuel elements [a]		
	Spacing	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$	Spacing	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
Dry	1 cm	0.8649 ± 0.0013	0.868	0 cm	0.5154 ± 0.0010	0.517
5%	1 cm	0.8937 ± 0.0011	0.896	0 cm	0.6334 ± 0.0010	0.635
10%	0.5 cm	0.9180 ± 0.0011	0.920	0 cm	0.7331 ± 0.0012	0.736
15%	0.5 cm	0.9412 ± 0.0012	0.944	0 cm	0.8138 ± 0.0012	0.816
Saturated	0 cm	0.9662 ± 0.0013	0.969	0 cm	0.8764 ± 0.0012	0.879

[a] See reference 1 for complete calculations and results.

Next the number of elements in the triangular-pitched array was reduced to as few as twelve. Cases were also run with a 0.9525-cm thick steel cylinder placed around the array, with the array approximately centered. This cylinder simulated the DOE SNF canister. The cylinder had a 43.815-cm inner diameter for 16 or fewer elements. For 17 to 19 elements, the cylinder inner diameter was increased to 44.450-cm to accommodate the whole array. Calculated results are given in Table 8. From this series of calculations, it is clear that the triangular-pitched array of 19 elements is more reactive than the regular arrangement evaluated earlier. But, the DOE SNF canister inner diameter is too small to allow a triangular-pitched array of 17 or more elements.

Table 8. Calculated results for triangular-pitched arrays

# of elements	Water reflection (no SS can) [a]		0.9525-cm SS, water reflection [a]	
	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
19	0.9662 ± 0.0013	0.969	0.9361 ± 0.0011	0.938
18	0.9436 ± 0.0012	0.946	0.9160 ± 0.0012	0.918
17	0.9185 ± 0.0011	0.921	0.8915 ± 0.0012	0.894
16	0.9012 ± 0.0011	0.903	0.8808 ± 0.0013	0.883
15	0.8816 ± 0.0012	0.884	0.8614 ± 0.0011	0.864
14	0.8638 ± 0.0012	0.866	0.8510 ± 0.0011	0.853
13	0.8303 ± 0.0011	0.833	0.8181 ± 0.0012	0.821
12	0.8144 ± 0.0012	0.817	0.8097 ± 0.0012	0.812

[a] See reference 1 for complete calculations and results.

<u>DOE SNF canister in co-disposal waste package</u>. The regular arrangement of 19 elements in the DOE SNF canister was placed inside the central support tube of the co-disposal waste package. The 5 outer storage positions contained HLW glass-pour canisters, as described in Section 2. It was determined that placement of the DOE SNF canister within the central support tube did not appreciably affect the calculated results. The water content in the co-disposal waste package and the DOE SNF canister was varied. This included varying the

water density in the co-disposal waste package, with the DOE SNF canister fully flooded. Calculated k_{eff} was greatest for the DOE SNF canister fully flooded, and the co-disposal waste package dry. Calculated k_{eff} was also obtained for the 15-element triangular-pitched array under the same conditions.

19 elements: $k_{eff} \pm 1\sigma = 0.9437 \pm 0.0008$, $k_{eff} + 2\sigma = 0.945$

15 elements: $k_{eff} \pm 1\sigma = 0.8849 \pm 0.0009$, $k_{eff} + 2\sigma = 0.887$

<u>Degraded fuel region</u>. These calculations used either the explicit model of the DOE SNF canister (in the co-disposal waste package), or a simple can of identical diameter, wall thickness, and length (with water reflection only). The can was modelled lying on its side, with the three axial regions of the fuel element maintained. Graphite and water were mixed homogeneously for the upper and lower regions. For the central portion, fuel region materials – sleeve, fuel annulus, and spine – were mixed homogeneously with water. The amount of water in the fuel region was reduced by decreasing the diametrical height of the mixture, while conserving the mass of fuel region materials. The vacated space above the mixture was filled with water. Cases were run for 13 to 19 elements. Maximum calculated k_{eff} results for each set of runs is given in Table 9. In the co-disposal canister, 15 degraded elements yields $k_{eff} + 2\sigma$ of 0.95.

Table 9. Calculated results for degraded fuel region

# of elements	Fuel mixture in can [a]			Canister in waste package [a]		
	height, cm	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$	height, cm	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
19	41.182	0.9770 ± 0.0011	0.979	43.815	1.0169 ± 0.0009	1.019
17	40.343	0.9535 ± 0.0012	0.956	40.343	0.9872 ± 0.0008	0.989
16	39.897	0.9392 ± 0.0011	0.941	*Not calculated*		
15	36.775	0.9196 ± 0.0011	0.922	36.775	0.9484 ± 0.0007	0.950
14	34.154	0.8989 ± 0.0011	0.901	34.154	0.9251 ± 0.0008	0.927
13	34.909	0.8744 ± 0.0011	0.877	31.771	0.8989 ± 0.0008	0.901

[a] See reference 1 for complete calculations and results.

Composition Sensitivity. As indicated previously, the composition as modelled for calculations included average EOL values for all isotopes except ^{233}U and ^{235}U, which were maximum EOL values. This is not necessarily the most conservative composition when evaluating fuels with burnup and breeding. BOL ^{235}U, EOL ^{233}U, and EOL Pu loadings are most conservative and easiest to defend. Using the 15-element array given in Figure 2, a comparison of various compositions was made. Results are shown in Table 10. These indicate that the composition as modelled for calculations, #1, is conservative compared to #2 and #3. However, compositions #4 and #5 are clearly more reactive. For 15 intact elements, calculated k_{eff} well below 0.90 for all compositions. For 15 elements in degraded condition, composition #5 yields calculated k_{eff} greater than 0.95. The geologic repository calculations typically take credit for the presence of geothite for fuel in degraded condition.[5] Composition #6 shows that if credit is taken for 50 kg of iron from internal steel, in the form of geothite, and its displacement of water, calculated k_{eff} decreases considerably. Internal steel may also decrease the calculated k_{eff} for the intact elements.

A calculation was done using composition #5 and 14 elements in degraded condition in the waste package. This yielded calculated k_{eff} of 0.954. Because internal structures for the DOE SNF canister have not yet been defined, these results indicate that the fissile loading limit for the DOE SNF canister is 13 Peach Bottom elements.

Table 10. Calculated results for composition comparison

Fuel Composition Description	15 intact elements in a SS can [a]	15 elements in degraded condition, canister in waste package [a]
	$k_{eff} + 2\sigma$	$k_{eff} + 2\sigma$
1. As modelled for calculations: maximum EOL ^{233}U & ^{235}U, average EOL all other isotopes	0.864	0.950
2. BOL fuel composition	0.852	*Not calculated*
3. As for #1, except ^{233}U omitted (BOL), and BOL ^{235}U	0.852	*Not calculated*
4. As for #1, except BOL ^{235}U	0.877	*Not calculated*
5. maximum EOL ^{233}U, BOL ^{235}U, average EOL ^{232}Th and Pu	0.884	0.977
6. As for #5, except 50 kg iron in the form of geothite added	*Not applicable*	0.883

[a] See reference 1 for complete calculations and results.

7.0 Design Features (Passive & Active) and Administratively Controlled Limits & Requirements

The design features important to the results of this analysis are given below.

- The DOE SNF canister is designed so that it maintains reasonable geometric integrity.
- No more than 14 Peach Bottom elements can be loaded into the DOE SNF canister.
- The nominal DOE SNF canister outer diameter is 45.7-cm (18.0-in.).
- The nominal DOE SNF canister inner diameter is 43.815-cm (17.25-in.).
- The nominal DOE SNF canister wall thickness is 0.953-cm (0.375-in.).

Based on this analysis, DOE SNF canisters loaded with Peach Bottom fuel must be handled, transported, and stored such that interaction with other fissile material is precluded.

8.0 Summary & Conclusions

Calculations were completed for Peach Bottom fuel elements in the small-diameter, 456.9-cm-long DOE SNF canister. The fuel elements were bare. No canister internals were considered. The maximum number of fuel elements that could fit into the canister is theoretically 19, but realistically only 14 or 15. Assuming BOL ^{235}U and maximum EOL ^{233}U, the calculated results are:

15 intact elements in the DOE SNF canister, $k_{eff} + 2\sigma = 0.884$;
15 elements in degraded condition in the co-disposal waste package, $k_{eff} + 2\sigma = 0.977$;
14 elements in degraded condition in the co-disposal waste package, $k_{eff} + 2\sigma = 0.954$.

If 50 kg of iron in the form of geothite is added, $k_{eff} + 2\sigma = 0.883$ for 15 elements in degraded condition in the co-disposal waste package.

Based on these results, the recommended fissile loading for the DOE SNF canister is 13 Peach Bottom fuel elements if no internal steel is present, and 15 Peach Bottom fuel elements if credit is taken for internal steel.

These calculations assume that the DOE SNF canister maintains reasonable geometric integrity during loading, handling, and drop configurations, depending primarily upon the canister wall thickness. This analysis does not conclusively address all loading, handling, and drop configurations, since these have not yet been defined.

9.0 References

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